

# PRE-CLUSTER DYNAMICS IN MULTIFRAGMENTATION

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The initial production and dynamical expansion of hot spherical nuclei are examined as the first stage both in the projectile-multifragmentation and in central collision processes. The initial temperatures, which are necessary for entering the adiabatic spinodal region, as well as the minimum temperatures and densities, which are reached in the expansion, significantly differ for hard and soft equations of state. Additional initial compression, occurring in central collisions leads most likely to a qualitatively different multifragmentation mechanism. Recent experimental data are discussed in relation to the results of the proposed model.

## 1 Introduction

Spinodal instabilities as a possible mechanism of multifragmentation was first suggested by Bertsch, Siemens and Cugnon<sup>1,2</sup>. Recent data from the ALADIN and FOPI experiments<sup>3,4,5,6</sup> shed some light on such a possible explanation. In particular the discovery of the caloric curve<sup>6</sup>, which looks like the one for a liquid-gas phase transition in water, suggests to study the mechanism of spinodal decomposition in more detail.

The expansion of the excited (projectile) residue can be regarded as the first stage in the multifragmentation process. For large enough initial excitation energies and temperatures the nuclear matter of the residue reaches states of mechanical volume instability, where small density fluctuations grow exponentially<sup>7,8,9</sup>. For an illustrative analysis of the instability evolution we refer to ref.<sup>10</sup>. The fragmentation process itself has been studied within molecular dynamics<sup>11,12,13,14</sup>. Studies by Friedman<sup>15,16</sup> within an expanding emitting source model (EES) show that intermediate mass fragments (IMFs) are indeed created within time intervals of about 50 fm/c indicating a simultaneous breakup of the residue.

We have been investigating, already for some time now<sup>17</sup>, the expansion dynamics of spherical hot nuclei for peripheral collisions. For low initial excitation energies one obtains monopole vibration with the largest possible amplitudes. Around an initial temperature of 5 MeV (i.e.  $E^*/A = 2$  MeV) the matter inside the expanding drop reaches, e.g. in the  $T, \rho$  plane, the boundary of the spinodal regime. The important feature at higher initial excitation energies is the occurrence of turning points deep in the spinodal region. The system stays long enough around these turning points, which all are located around  $T = 4$  MeV, such that instabilities can develop and fragments can be

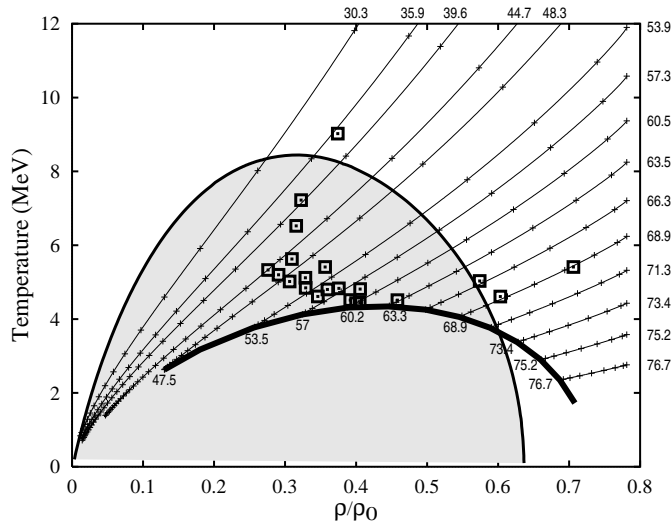


Figure 1: Time evolution of the Au residue for a soft equation of state in a peripheral collision (without initial compression) in the temperature – density plane. The crosses on the trajectories indicate time steps of 5 fm/c. The shadowed zone corresponds to the adiabatic mechanical instability region for infinite nuclear matter. The numbers give the charge numbers initially and at the turning points which are connected by the heavy solid line. The open boxes denote the experimental data<sup>6</sup> (without error bars).

formed. At initial temperatures  $T > 12$  MeV the system runs through the freeze-out density of  $0.3\rho_0$  before reaching a turning point.

## 2 The Model

In this section we describe a few essential features of the model. A more detailed description of the model will be published elsewhere<sup>18</sup>.

First we study the peripheral collision setup. We start out from a thermalized spherically symmetric projectile-like nucleus at ground state density, which has been created in the peripheral high-energy collision according to the abrasion model<sup>19,20,21</sup>. The typical temperature for such a hot nucleus is not too high, such that the mean free path of nucleons is still comparable or even larger than the size of the system<sup>22</sup>. Thus, we can approximately assume homogeneity in density and temperature for the expanding nucleus.

During the expansion the hot nucleus evaporates particles. We consider

only neutron and proton evaporation. Deuterons may be considered to arise from coalescence of nucleons. We follow the evolution of the excited remnant and plot the trajectories in the temperature – density plane.

If the excitation energy is high enough, the expansion leads into the instability region of the equation of state. For not too high excitation energies the expansion of the homogeneous system stops at a certain density. Around these turning points the system has enough time ( $\geq 30$  fm/c,<sup>7,9</sup>) to develop inhomogeneities in density, and subsequently decay into many fragments. The final mass and charge spectra is not given by this model, however some quantitative comparison with experiments concerning temperature and excitation energy (caloric curve) can be made.

For a central collision setup we considered a somewhat similar scenario. Here the initial expanding source can achieve much higher initial temperatures, and also one should take into account compression. The initial state was estimated on the base of the shock model<sup>23</sup>. Due to the compression the evolution of such a system is so fast, that the evaporation can be neglected (the “evaporated” particles cannot leave the excited source), and except very low excitation energies no turning is obtained. The calculation is stop at the break-up density of  $0.3\rho_0$  obtained from analyzing the ALADIN data.

### 3 Results

According to the abrasion model<sup>21</sup>, the initial excitation energy (temperature) is correlated with the charge number of the projectile residue. These numbers are given on the right and upper parts of Fig. 1. The calculated expansion trajectories in the  $(T, \rho)$ -plane are significantly different for a soft and a stiff equation of state (EOS).

We follow the trajectories up to their turning points if reached within 200 fm/c. The turning points are indicated by the heavy solid lines. Turning points exist for initial temperatures up to about 14 MeV. We notice that the turning points for the same initial excitation lie one to two MeV in temperature and  $0.1\rho_0$  to  $0.2\rho_0$  in density higher for the stiff EOS as compared to the soft one. Moreover, we see that the turning points are located almost at the same temperatures independent of the initial excitation, i.e. around 4 MeV and 5 MeV for the soft and hard EOS, respectively. This plateau does not move if one changes the initial excitation energy, the only effect is, that the charge numbers become different initially and at the turning points.

A natural criterion for multifragmentation to occur, is whether the system reaches the region of volume instability (adiabatic spinodal region), where the

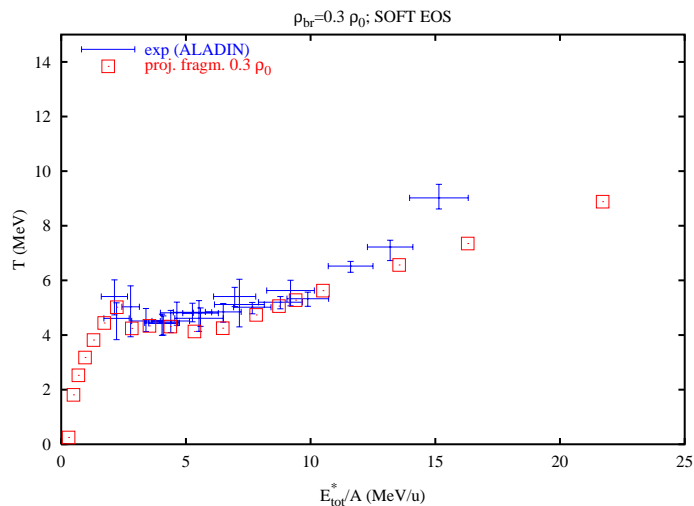


Figure 2: The caloric curve as deduced by the ALADIN collaboration<sup>6</sup> (crosses) compared with the pre-cluster condition. The total excitation energy includes flow energy which is significant in the isentropic dynamics for  $E^*/A > 15$  MeV. The discrepancy at large excitation energies may therefore indicate that dissipation is not negligible during the expansion process.

derivative of the pressure with respect to the density along an adiabat becomes negative. Since the system is closed we consider the adiabatic process to be the relevant one. In Fig. 1 the region of instability is shadowed and bounded by the spinodal. To enter the spinodal region and stay there for more than 30 fm/c one needs initial temperatures of about 8 MeV and 11 MeV for the soft and hard EOS, respectively.

Because of the occurrence of turning points in the expansion, the multifragmentation process of the projectile residue has a unique feature: the subsequent decay into fragments is expected to be rather free from collective flow. This is different from the fragmentation of compressed compound systems which are formed in central collisions. As our calculations show already for a small initial compression ( $1.5 \rho_0$ ) no turning points occur for realistic initial excitation energies. Thus the fragmentation process becomes qualitatively different and looks more like an explosion<sup>24</sup>.

In Fig. 2 we compare our results for the temperature and the total excitation energy in the remnant with experimental data from the ALADIN experiment. Our points are determined at the turning points if the corresponding

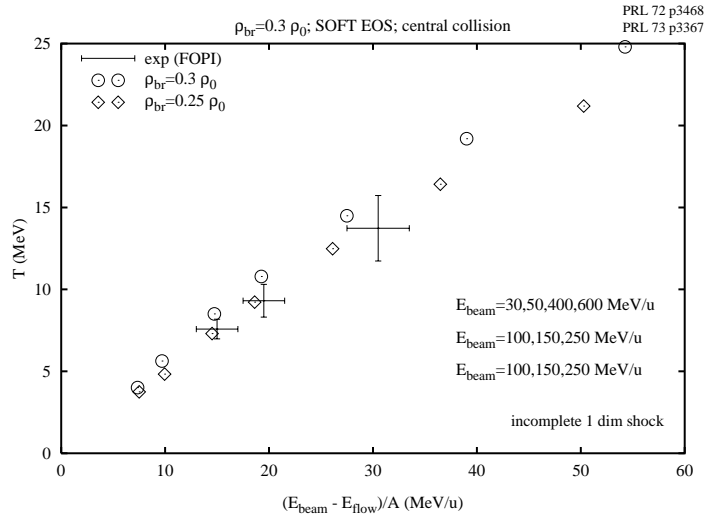


Figure 3: The caloric curve as deduced from the FOPI experiments at 100, 150 and 250 MeV/u collisions<sup>4,5</sup> (crosses) compared with our results (circles for  $\rho_{br}=0.3 \rho_0$  and diamonds for  $\rho_{br}=0.25 \rho_0$ ). The flow energy is subtracted from the excitation energy.

density is higher than  $\rho_{br} \approx 0.3\rho_0$ , or at the break-up density otherwise. For very low excitation energies the average values of the vibration are chosen. There are some deviation at high excitation energies, which is due to the arising flow energy in our model.

In Fig. 3 the comparison with the FOPI data<sup>4,5</sup> are plotted. The experimental results are consistent with the expansion dynamics of an initially compressed nucleus and a break-up density of  $0.3\rho_0$ .

Figs. 2 and 3 show another important difference between peripheral and central collisions. For high excitation energies both curves follow the  $T = \frac{2}{3}E_{kin}/A$  free gas limit shifted by the remaining binding energy. However at low energies the peripheral setup shows a phase-transition like behavior: with decreasing excitation energy the temperature stays constant, and at even lower energies the nuclear liquid relation is reproduced.

We conclude that to a large extent the temperatures observed in multifragmentation can be understood from the expansion dynamics into the spinodal regime and across the freeze-out density both for peripheral and for central collisions, despite the different break-up mechanism. The observed "phase-transition" plateau depends on the initial compression of the remnant, and for

usual central collision is missing.

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